DESIGN AND IMPLEMENTATION OF DOUBLE FREQUENCY BOOST CONVERTER

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***Abstract*- Improving the efficiency and dynamics of power converters is concerned tradeoff in power electronics. The increase of switching frequency can improve the dynamics of power electronics, but the efficiency may be degraded.A double frequency Boost converter is proposed to address this concern. This converter is comprised of two Boost cells: one works at high frequency, and another works at low frequency. To operate at high frequency, converter performance is improved and at low frequency, efficiency is improved. So both converter performance and efficiency is improved by a double frequency Boost converter. . It operates in a way that current in the high-frequency switch is diverted through the low-frequency switch. Thus the converter can operate at very high frequency without adding the switching loss of the converter remains small. Simulation results demonstrate that the proposed converter greatly improves the efficiency and exhibits nearly the same dynamics as the conventional high frequency Boost converter.**

Key words - Boost, Double frequency Boost, Efficiency

1. INTRODUCTION

In order to improve the transient and steady state performance of power converters and to enhance power density, high switching frequency is an effective method. However, switching frequency rise causes higher switching losses and greater electromagnetic interference. This in turn, limits the increase of switching frequency and hinders the improvement of system performance. Active and passive soft-switching techniques have been introduced to reduce switching losses.

Switching losses are more in DC-DC converter. To reduce the Switching losses, Switching techniques are used. There are two types of Switching techniques1.Hard Switching 2.Soft Switching. Soft Switching namely Zero Voltage Switching and Zero Current Switching[1-2]. The major disadvantage of ZVS and ZCS is that they require variable-frequency control to regulate the output. This is undesirable since it complicates the control circuit and generates unwanted EMI harmonics, especially under wide load variations. Interleaved Converter is only option to reduce the harmonics, and to achieve higher efficiency [3]. The major disadvantage of Interleaving technique is Circulating current problem. To overcome the Circulating current problem, a newly proposed converter namely Double frequency Boost Converter is introduced.

This paper proposes a novel converter topology to achieve high dynamics response and high efficiency of Boost converter. This topology consists of a high frequency Boost cell and a low frequency Boost cell; and call it the “Double Frequency Boost converter” (DF Boost).

Double frequency Boost converter consists of two Boost cells: one works at high frequency, and another works at low frequency. To operate at high frequency, converter performance can be improved and at low frequency efficiency can be improved. Both efficiency and converter performancecan be improved by Double Frequency Boost converter.It operates in a way that current in the high-frequency switch is diverted through the low-frequency switch. On the other hand, high frequency switching converter in parallel with low frequency converter enhances the output voltage response. The interleaved operation employs N converters to operate in parallel with interleaved clocks, so the total dynamics can reach higher performance. Multi converter paralleling method, which employs low power converters in parallel to enhance the power rating, has been proposed to enhance the power processing capability. Moreover, the parallel structure brings about the circulating current problem[4-5].Additional current sharing control is need to overcome this problem.

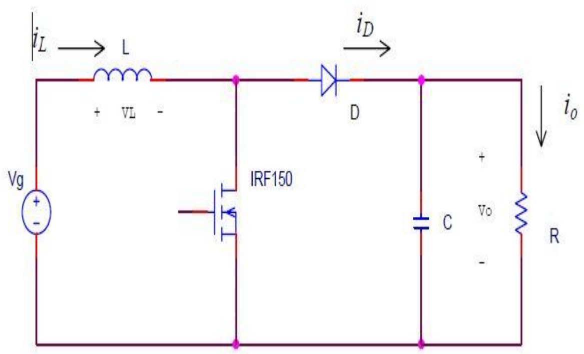

Fig.1. Schematic diagram of Boost converter

2, PROPOSED DOUBLE FREQUENCY BOOST CONVERTER

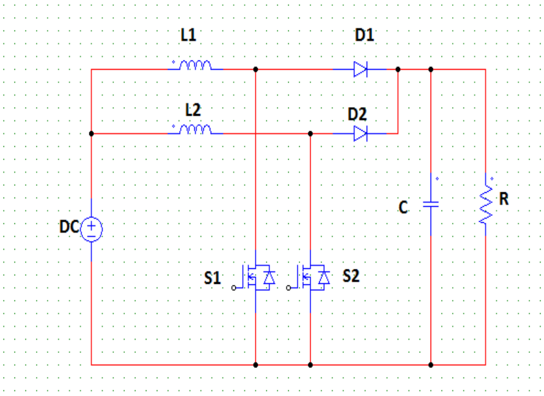

Fig. 2. Schematic diagram of Double Frequency Boost converter

The topology of a conventional Boost converter is shown inFig. 1. In the steady state,the input (V_S) and the output (V_O) of the converter are governed by

$$V_{0}=\frac{V_S}{1-d} \quad (1)$$

Where, dis the duty ratio.From the above relation(1), we can find the output voltage of double frequency Boost converter. It is same as a boost converter. If the Boost converter works in the continuous conduction mode, then the inductor current $I_L$can be regarded as a current source. In each switching cycle, both the current flowing through the switch and the voltage across the diode is averaged.

In this paper, the proposed converter is called the DF Boost converter, because these Boost cells work at two different frequencies. The cell containing L1, S1 and D1 works at higher frequency, and is called the high-frequency Boost cell. Another cell containing L2, S2 and D2 works at lower frequency, and is called the low frequency Boost cell. The high frequency Boost cell is used to enhance the output performance, and the low-frequency Boost cell to improve the converter efficiency. An active switch, instead of a diode as in the conventional unidirectional Boost converter, is employed to realize D1 in the high-frequency Boost cell. This active switch transfers the energy stored in the low-frequency cell to the source during the transient stage of load step-down.

It works complementarily with high-frequency cell switch S1, and improves the transient response. The switch S1is controlled to operate at the high frequencyf_h, and the corresponding switching period is T_{sh}. On the other hand, the switch S2is controlled to work at a low frequencyf_l, and the corresponding switching period isT_{sl}. Assume that the high frequency is an integer multiples of the low frequency, i.e.

$$f_h=Mf_l \quad (2)$$

At each low-frequency cycle, four switching states exist. Table I lists the switching states according to the status of switches S1 and S2.

Table 1, Switching States

Mode	S1	S2
1	ON	ON
2	ON	OFF
3	ON	ON
4	OFF	ON

2.1 Mode 1: S1 ON, and S2 ON

The circuit operation of Double Frequency Boost converter is split up into four modes of operation is depicted in Table 1. In mode 1 operation, both switches S1 and S2 are ON and diodes D1 and D2 are OFF. The voltage and current equations are expressed in equations (3)-(5).

$$V_s=V_{L1} \quad (3)$$
$$V_S=V_{L2} \quad (4)$$
$$-\,i_c=i_o \quad (5)$$

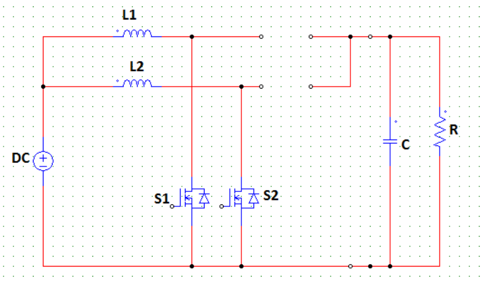

Fig. 3. Mode 1 circuit for DF Boost converter

In this state, the voltage V_{L1}across the inductor L1 is positive, hence the current I_{L1}flowing through L1rises, and the current I_{L2}flowing through L2 does not change.

2.2 Mode 2:S1 ON, and S2 OFF

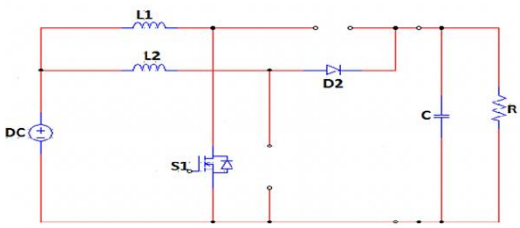

Fig. 4. Mode 2 circuit for DF Boost converter

The mode 2 diagram of Double Frequency Boost converter is shown in Fig. 4. The voltage and current equations for mode2 is expressed in equations (6)-(8).

$$V_S = V_{L1} \quad (6)$$
$$V_{L2} = V_S - V_0 \quad (7)$$
$$i_c = i_{L2} - i_o \quad (8)$$

In the mode 2 operation, the Switch S_1ON and S_2 OFF and diode D_1OFF and D_2 ON. The voltage across the inductor $L_1$is equal to the supply voltage. The voltage across the inductor L_2 is equal to the supply voltage minus the load voltage.The voltage V_{L1} across $L_1$is positive, so the current I_{L1} rises. Since the voltage V_{L2} across L_2 is negative, the current I_{L2} through L_2 decreases. The current across the capacitor is equal to the current across the inductor L_2 minus the load current.

2.3 Mode 3: S1 ON, and S2 ON

In mode 3 operation, both switches S1 and S2 are ON and diodes D1 and D2 are OFF. The voltage and current equations for mode 3 is expressed in equations (9)-(11). The equivalent circuit equations are derived as

$$V_S = V_{L1} \quad (9)$$
$$V_S = V_{L2} \quad (10)$$
$$-i_c = i_o \quad (11)$$

In this state, the voltage V_{L1}across the inductor L1 is positive, hence the current I_{L1}flowing through L1 rises, and the current I_{L2}flowing through L2 does not change.

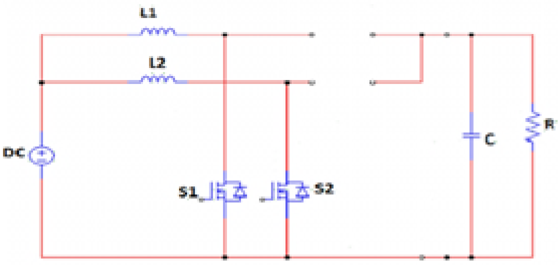

Fig. 5. Mode 3 circuit for DF Boost converter

2.4 Mode 4: S1 OFF, and S2 ON

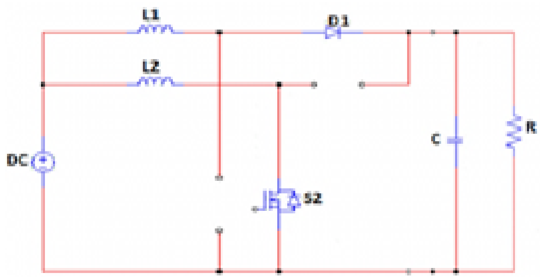

Fig. 6. Mode 4 circuit for DF Boost converter

Finally,In the mode 4 operation, the Switch S_1 OFF and S_2 ON and diode D_1ON and D_2 OFF. The voltage across the inductor L_1 is equal to the supply voltage minus the load voltage. The voltage across the inductor L_2 is equal to the supply voltage. The current across the capacitor isequal to the current across the inductor L_1 minus the load current.

$$V_S = V_{L2} \quad (12)$$
$$V_{L1} = V_S - V_0 \quad (13)$$
$$i_c = i_{L1} - i_0 \quad (14)$$

The designed Double Frequency Boost converter is described in Table 2.

Table 2, Design parameters

Parameter	Values
Input voltage(V_s)	8V
Output voltage(V_0)	16V
Output power(P_0)	10W
Ripple voltage (ΔV_c)	0.070
Ripple current(ΔI_l)	0.95
High frequency inductor (L1) for F_h=100KHZ	42.10μH
Low frequency inductor (L2) for F_l=10KHZ	421μH
Output capacitance	44μF
Resistance(R_0)	26Ώ

3. DESIGN OF DOUBLE FREQUENCY BOOST CONVERTER

Simulink diagram of Double Frequency Boost converter using Matlabis depicted as shown in Fig. 7. A DF Boost, a single high-frequency Boost converter whoseswitching frequency is the same as the higher frequency of DF Boost, and a single low-frequency Boost converter whose switching frequency is equal to the lower frequency of DF Boost.

Table 3, Performance parameters of the open loop boost converters

Boost Converter	Settling Time (ms)	Peak Over-shoot (%)	Rise Time (ms)	Steady State Error (V)	Output Ripple Voltage (V)
Double frequency	12	60	1	0.02	0
High Frequency	5	80	0.05	0.05	less
Low frequency	24	79	3	0.04	more

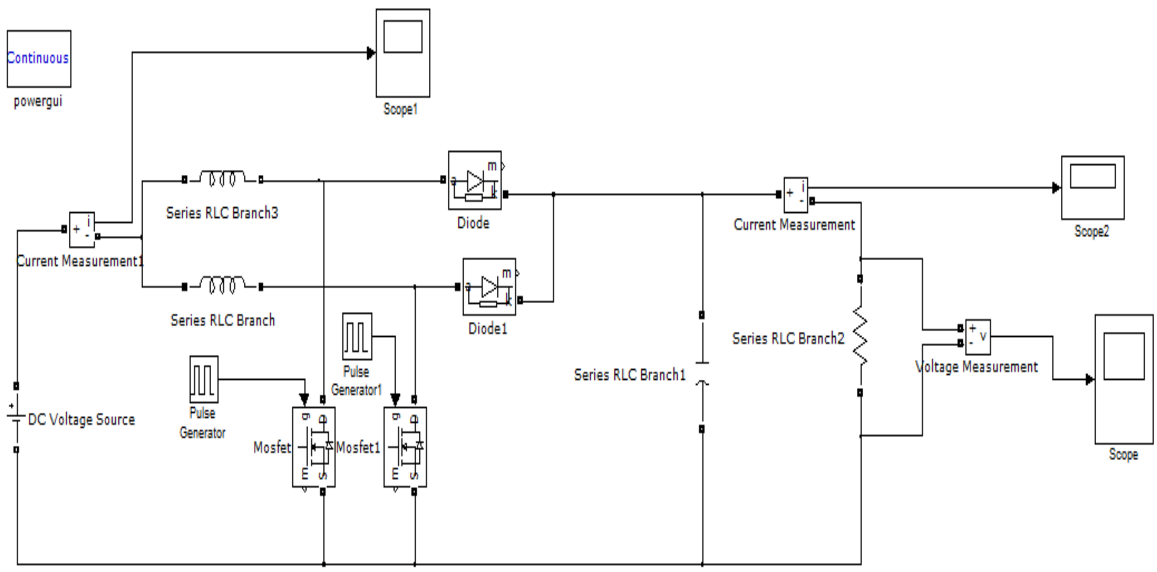

Fig. 7. Simulink diagram of Double Frequency Boost converter

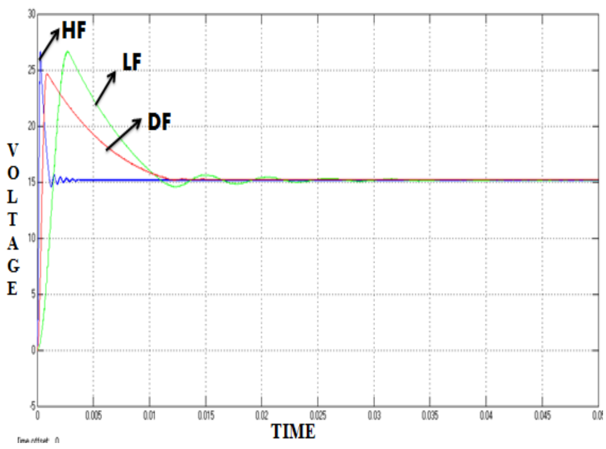

Fig. 8. Output voltage waveform of Boost converters

Fig. 8 shows the comparison of output voltage for Double Frequency Boost, high frequency Boost and low frequency Boost converter. In high frequency Boost converter,a peakovershoot is about 80% and its settling time is about 5ms.In low frequency Boost converter,a peakovershoot is about 79% and its settling time is about 24ms.In double frequency Boost converter,a peakovershoot is about 60% and its settling time is about 12ms. Table III shows the performance parameters of the DF Boost, high frequency Boost, and low frequency Boost are shown in Table III. The table III proves that the Double Frequency Boost performance is better than all other Boost converter.

3 MODELLING OF DOUBLE FREQUENCY BOOST CONVERTER

The Double Frequency Boost converter is modeled using state space averaging technique in which the design is carried out in time domain based on their performance indices. This method is highly significant for this kind of converters since the PWM converters are the special type of nonlinear systems which is switched in between two or more nonlinear circuits depending upon the duty ratio .The unique feature of this method is that the design can be carried out for a class of inputs such as impulse, step or sinusoidal function in which the initial conditions are also incorporates.The state vector of Double Frequency Boost Converter is given

$$\boldsymbol{x(t)} = \begin{bmatrix} \boldsymbol{i_{L1}} \\ \boldsymbol{i_{L2}} \\ \boldsymbol{v_c} \end{bmatrix} \quad (15)$$

where$i_{L1}$and i_{L2} are the current through an inductor L1and L2 respectively; V_c is the voltage across the capacitor C. For the given duty cycle d(k) for the kth period, the systems are illustrated by the following set of state space equations in continuous time domain :

$$\dot{\boldsymbol{X}} = \boldsymbol{Ax} + \boldsymbol{BV_s} \quad (16)$$

Where x is the state vector matrix, A is the state coefficient matrix and B is the source coefficient matrix, and d is a duty cycle is a function of x and Vs in a feedback system.

State model of an Double Frequency Boost converter is derived and is discussed below. High power densities are possible only for continuous conduction mode (CCM) of operation. Diode Dl and D2 are always in a complementary state with the switches S1and S2 respectively. When S1 - ON, D1 - OFF and vice versa and S2 - ON, D2 -

OFF vice versa. For the continuous conduction mode of operation, four modes of operations are possible, and state equations are

Mode 1: S1 is ON and S2 is ON

$$\dot{x} = A_1 x + B_1 V_1 \tag{17}$$

Mode 2: S1 is ON and S2 is OFF

$$\dot{x} = A_2 x + B_2 V_1 \tag{18}$$

Mode 3: S1 is ON and S2 is ON

$$\dot{x} = A_3 x + B_3 V_1 \tag{19}$$

Mode 4: S1 is OFF and S2 is ON

$$\dot{x} = A_4 x + B_4 V_1 \tag{20}$$

$$A_1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1/RC \end{bmatrix}; \quad B_1 = \begin{bmatrix} \frac{1}{L1} \\ \frac{1}{L2} \\ 0 \end{bmatrix}$$

$$A_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -1/L2 \\ 0 & 1/C & -1/RC \end{bmatrix}; \quad B_2 = \begin{bmatrix} \frac{1}{L1} \\ \frac{1}{L2} \\ 0 \end{bmatrix}$$

$$A_3 = A_1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1/RC \end{bmatrix}; \quad B_3 = \begin{bmatrix} \frac{1}{L1} \\ \frac{1}{L2} \\ 0 \end{bmatrix}$$

$$A_4 = \begin{bmatrix} 0 & 0 & -1/L1 \\ 0 & 0 & 0 \\ 1/C & 0 & -1/RC \end{bmatrix}; \quad B_4 = \begin{bmatrix} \frac{1}{L1} \\ \frac{1}{L2} \\ 0 \end{bmatrix}$$

Where

$$[A] = A_1 d_1 + A_2 d_2 + A_3 d_3 + A_4 d_4 \tag{21}$$

$$[B] = B_1 d_1 + B_2 d_2 + B_3 d_3 + B_4 d_4 \tag{22}$$

$$[u] = V_1 \tag{23}$$

Where d is the duty cycle ratio. d_1, d_2, d_3 & d_4 are the duty cycle of Mode 1, Mode 2, Mode 3 & Mode 4 respectively.

For the continuous conduction mode of operation, we have

$d_1 = d_3$; $d_2 = d_4$; $d_1 + d_2 = 0.5$; $d_1 + d_2 + d_3 = D$; $d4 = 1 - D$

Hence

$$A = \begin{bmatrix} 0 & 0 & \frac{-d_2}{L_1} \\ 0 & 0 & \frac{-d_2}{L_2} \\ \frac{d_2}{C} & \frac{d_2}{C} & \frac{-2d_1-2d_2}{RC} \end{bmatrix}; B = \begin{bmatrix} \frac{2d_1+2d_2}{L_1} \\ \frac{2d_1+2d_2}{L_2} \\ 0 \end{bmatrix}$$

By using A and B matrices, we have to find transfer function. Transfer function G(s)

$$= \frac{5.821e^{-11}s^2 + 2.969e^8 s - 0.0001217}{s^3 + 1.923e^5 s^2 + 1.485e^8 s + 1.674e^{-5}}$$

4 CLOSED LOOP OF DOUBLE FREQUENCY BOOST CONVERTER

In closed-loop control systems the difference between the actual output and the desired output is fed back to the controller to meet desired system output. Often this difference, known as the error signal is amplified and fed into the controller.

4.1 PID Controller

A proportional integral derivative controller (PID controller) is a control loop feedback mechanism widely used in industrial control systems. A PID controller calculates an error value as the difference between a measured process variable and a desired set point. PID Controllers are also known as three term controllers- Proportional,Integral and Derivative. **Proportional action**: responds quickly to changes in error deviation.**Integral action**: is slower but removes offsets between the plant's output and the reference.**Derivative action**: Speeds up the system response by adding in control action proportional to the rate of change of the feedback error.

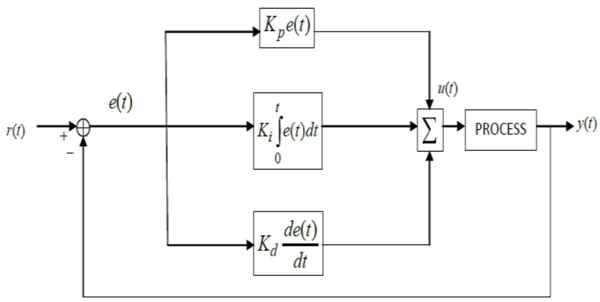

Fig. 9. Control Logic Of PID Controller

The proportional, integral and derivative term is given by:

$$u(t) = K_p e(t) + K_d \frac{d}{dt} e(t) + K_i \int_0^t e(t)\, dt \tag{24}$$

By using PID Controller, overshoot of the system is reduced and it improves the stability of the system.

5 Tuning Methods

Tuning a PID controller is setting the K_p, K_i, and K_d tuning constants so that the weighted sum of the proportional, integral, and derivative terms produces a controller output that steadily drives the process variable in the direction required to eliminate the error. The process of selecting the controller parameters to meet given performance specifications is known as controller tuning. Ziegler and Nichols method used for tuning PID controllers (for determining values of K_p, T_i and T_d) based on the transient response characteristics of a given plant.

6 Ziegler-Nichols Closed Loop Tuning

At the controller, select Proportional-only control, i.e. set K_p to the lowest value and T_i to infinity and T_d to zero.Adjust the controlled system manually to the desired operating point.Set the manipulated variable of the controller to the manually adjusted value and switch to automatic operating mode. Continue to gradually increase K_p until the controlled variable encounters harmonic oscillation. If possible, small step changes in the set point should be made during the K_p adjustment to cause the control loop to oscillate.Take down the adjusted K_p value as critical Proportional-action coefficient Kc_r.

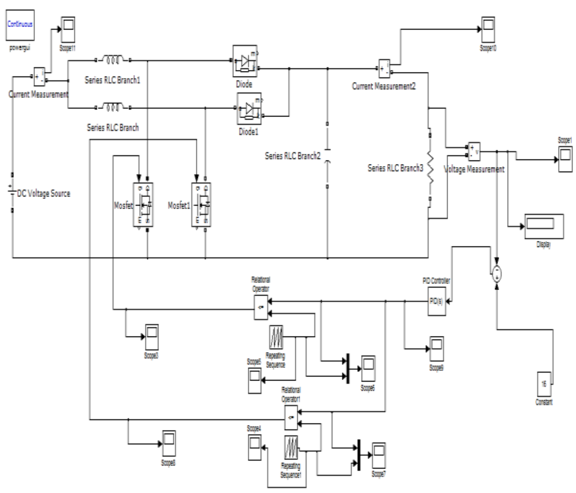

Fig. 10. Closed Loop Circuit Of Double Frequency Boost Converter

Determine the time span for one oscillation amplitude as Pc_r, if necessary by taking the time of several oscillations and calculating their average. $Pc_r = \frac{2\pi}{\omega}$, $\omega$is the crossover frequency. Once the value for $Kc_r$and $Pc_r$are obtained, the PID parameter can be calculated. $K_p = 0.6Kc_r$, $T_i = 0.5Pc_r$, $T_d = 0.125Pc_r$.After finding K_p, T_i, T_d then we have to calculate the values of derivative gain Constant K_d and integral gain constant K_i.The integral gain constant can be calculated as, $K_i = \frac{K_p}{T_i}$.The derivative gain constant can be calculated as, $K_d = K_p . T_d$.After finding K_p, K_i , K_d, substitute these values in PID controller for control the output voltage.

The cell containing L_1,S_1 and D_1 works at higher frequency, and is called the high-frequency boost cell. Another cell containing L_2, S_2 and D_2 works at lower frequency, and is called the low frequency boost cell. The input Voltage is 8V.L_1acts as a high-frequency inductor.L_2acts as a low frequency inductor. Two switches are connected in parallel and it is connected to a capacitance of 44µF and it is given to load resistance of 26Ω.The output voltage obtained is 16V.In the closed loop of Double Frequency Boost Converter,the variation in load, and the input parameters, but the output voltage is maintained to be constant.
The simulation circuit of closed loop of Double Frequency Boost Converter is shown in Fig.10

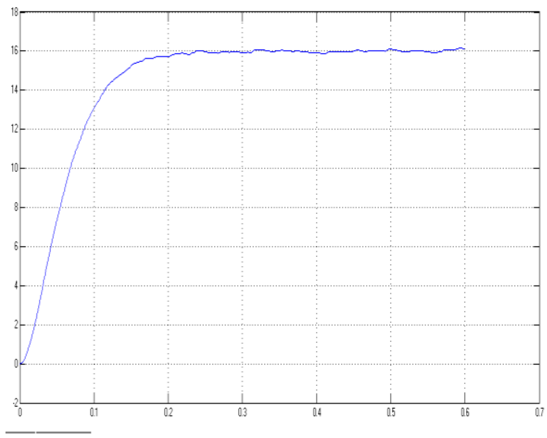

Fig. 11. Closed Loop output voltage response of Double Frequency Boost Converter

7. EFFICIENCY ANALYSIS

In order to analyze the efficiency improvement of the proposed DF Boost converter, the efficiency expression is analyzedin this section. The analysis is also applied to the single highfrequencyBoost and low-frequency Boost converters. Variousloss estimation methods have been proposed in the literaturebased on different assumptions [11-12] A simple loss modelis adopted here [13] in that want to show the efficiency relationship between the DF Boost and single high-frequencyBoost, not to develop a new loss model.

In the analysis, the following assumptions are made.
1) The conduction losses of active switch and diode areestimated, respectively, according to their conductionvoltages V_{on} and V_F.

2) The switching transient processes are assumed to satisfythe linear current and voltage waveforms. Moreover, theturn-on time t_{on} is the same for all switches and diodes,so is the turn-off timet_{off}.
3) Since the switching loss usually dominates the total loss,losses of the output capacitor and output inductor are not calculated here.

$$\text{Efficiency} = \frac{P_{in} - (P_{SWITCH}+P_{INDUCTOR}+P_{DIODE})}{P_{in}} \quad (25)$$

$$P_{SWITCH} = R_{NMOS} \times D\times (I_{OUT}/1 - D)^2 \quad (26)$$

$$P_{INDUCTOR} = R_L \times (I_{OUT}/1 - D)^2 \quad (27)$$

$$P_{DIODE} = R_D \times I_{OUT}^2 + VF\times I_{OUT} \quad (28)$$

In a single-frequency Boost converter, the total loss P_{SF} comes from four parts, the conduction lossP_{scon} and switchingloss P_{SS} of the active switch S, and the conduction loss P_{dcon} and switching loss P_{sd} of the diode. When the input voltage is V_{in}, duty ratio is d, the inductor average current isI_L, and theswitching frequency is f_s, the losses can be estimated accordingto the following equations [13].

$$P_{scon} = dV_{on}I_L \quad (29)$$

$$P_{dcon} = (1-d)V_F I_L \quad (30)$$

$$P_{ss} = \frac{1}{2} f_s V_{in} I_L (t_{on} + t_{off}) \quad (31)$$

$$P_{sd} = \frac{1}{2} f_s V_{in} I_L (t_{on} + t_{off}) \quad (32)$$

The losses in high frequency cell

$$P_{sconH} = 0.5D.V_{on}I_{Lh} \quad (33)$$

$$P_{dconH} = 0.5(1-D).V_F I_{Lh} \quad (34)$$

$$P_{ssH} = \frac{1}{4} f_h V_{in} I_{Lh} (t_{on} + t_{off}) \quad (35)$$

$$P_{sdH} = \frac{1}{4} f_h V_{in} I_{Lh} (t_{on} + t_{off}) \quad (36)$$

The losses in low frequency cell

$$P_{sconL} = D.V_{on}(I_L - 0.5I_{Ll}) \quad (37)$$

$$P_{dconL} = (1-D).V_F(I_L - 0.5I_{Ll}) \quad (38)$$

$$P_{ssL} = \frac{1}{2} f_1 V_{in}(I_L - 0.5I_{Ll})(t_{on} + t_{off}) \quad (39)$$

$$P_{sdL} = \frac{1}{2} f_1 V_{in}(I_L - 0.5I_{Ll})(t_{on} + t_{off}) \quad (40)$$

Then from(29)-(40),the total conduction loss P_{conDF}in the DF boost is approximately the same as that in the single frequency boost converter

Total conduction loss in Double Frequency Boost converter.

$$P_{conDF} \approx P_{scon} + P_{dcon} \quad (41)$$

In the case the low-frequency inductor current is small with reference to the inductor average current, the total switching loss P_{sDF} can be approximated as

Total switching losses

$$P_{sDF} \approx f_1 V_{in} I_L (t_{on} + t_{off}) \quad (42)$$

It follows from (33)–(42) that the total conduction loss of DF boost converter is the same as the single frequency boost converter. This result also can be reasoned from the fact that the total currents flowing through the DF boost switches and diodes are the same as that through a single-frequency boost. On the other hand, the total switching loss is nearly the same as the single low-frequency boost, and is much smaller than that of the single high-frequency boost. Hence, the DF boost converter improves the efficiency by current diversion to the low-frequency boost cell.

The efficiency of the Double Frequency Boost, low frequency Boost and high frequency Boost are illustrated in Fig. 12. From the graph one can understand that the high frequency Boost converter has less efficiency than the other two Boost converters. The efficiency of the low frequency Boost and double frequency Boost are almost same.

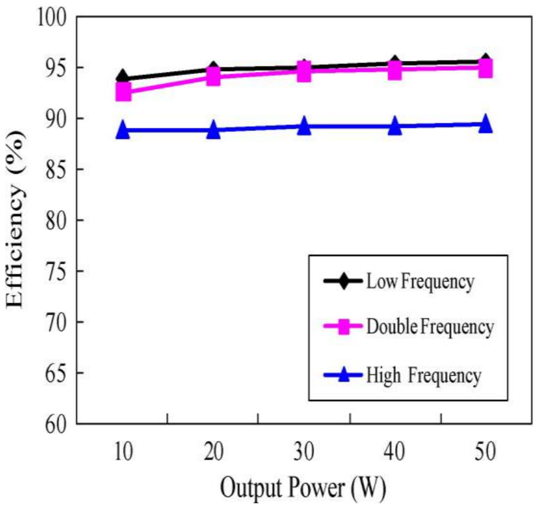

Fig.12. Efficiency of the Boost converters

From the above results, the Double Frequency Boost converter not only improve the performance of the Boost converter and also improve the efficiency of the Boost converter is evident.

8. CONCLUSION

This paper has presented a novel topology of Double Frequency Boost converter. Analytical results have demonstrated that the DF Boost converter not only exhibits the same steady state and transient performance but also improves the efficiency of conventional Boost converters. The proposed converter does not need the load transient change information for accurate current control and does not have the current circulating problem and it is used for high power applications. Extension to double-frequency switch-inductor three-terminal network has also been described. Future work will investigate whether the proposed Boost converter is applicable for Electric Vehicle and PV cell applications

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